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Assessing the impact of drought on the emissions- and water-intensity of California's transitioning power sector

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ABSTRACT

This study investigates how technological transitions across California's power sector have shifted its state-level carbon dioxide emissions and cooling water consumption intensities. Its ultimate goal is to evaluate how the state's climate mitigation and environmental policies have affected the power sector's vulnerability to extreme drought and how extreme drought has affected progress towards the state's climate mitigation priorities. The study analyzes the period spanning 2010–2016, which includes one of the state's most severe droughts on record. The results indicate that the growth of variable renewable energy generation has helped offset some of the negative consequences of drought, which include increased emissions and cooling water usage by natural gas generators during periods of low hydropower. However, the retirement of the San Onofre nuclear power plant has delayed the overall decarbonization of the state's power sector, and the closure of significant coastal power plant capacity could increase the freshwater consumption of the power sector if replacement capacity is not cooled with alternative cooling water sources or dry cooling systems. The noted tradeoffs between greenhouse gas mitigation priorities, freshwater dependency, and vulnerability to climatic events highlight the importance of holistic decision making as regional power grids transition to cleaner generation sources.

1. Introduction

California has been a leader in enacting policies to reduce the climate change and environmental consequences of power generation across the state. Recent regulations have been passed to reduce statewide greenhouse gases (California Legislative Information, 2006; California Legislative Information, 2017a; Office of Governor, 2015), increase the development of renewable energy (California Legislative Information, 2017b), decrease the impacts of power plant cooling systems on aquatic ecosystems (California State Water Resources Control Board, 2010), and promote demand-side interventions such as demand response and energy efficiency (California Legislative Information, 2006; California Public Utilities Commission and California Energy Commission, 2008; California Energy Commission, 2017a). Collectively, these policies have led to large technological transitions in electricity generation units across the state, away from large, inefficient thermal power generators, towards more efficient natural gas combined cycle and renewable generators (California Energy Commission, 2017d).

At the same time, unprecedented drought between 2012 and 2016 challenged the operation of some of California's electricity generation infrastructure, especially those generators with large freshwater dependencies, namely hydropower (Belmecheri et al., 2016; Gleick, 2017). Even in the period prior to the recent drought, an analysis assessing the lifecycle water use across California's energy system between 1990 and 2012 using an input-output method, concluded that California has higher water and CO_2 footprints when regional hydroelectricity capacity is reduced (Fulton and Cooley, 2015). More generally, drought events have been recognized in the literature for exacerbating the power grid's vulnerability to disruptions (Voisin, 2016; Kern and Characklis, 2017), increasing risks of insufficient generation (particularly during periods of peak summer demand) (Voisin, 2016; Kimmell et al., 2009), and increasing electricity-related carbon dioxide (CO_2) emissions (Hardin, 2017; Turner et al., 2017). These drought events have also been associated with increased electricity generation costs (Kern and Characklis, 2017; Gleick, 2016), as well as the social costs associated with power generation (Gleick, 2017; Eyer and Wichman, 2016).

Opportunities to support adaptation and resiliency strategies in the power sector to reduce these climate-induced vulnerabilities have also been addressed in literature (Miara et al., 2017; Pfenninger et al., 2014; Koch and Vögele, 2009), mostly for Western Interconnection and Texas

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(Harto et al., 2012; Bartos and Chester, 2015; Fowler and Shi, 2016). In a recent California-based study, Hardin et al. estimated that 22 million more metric tons of CO_2 were emitted from California's power sector during 2012–2014 drought compared to the period spanning 2009–2011, which is equivalent to a 33% increase in its annual CO_2 emissions compared to 2011 (Hardin, 2017). They conclude that increasing solar photovoltaic panels (PV) and wind renewables by 250% of their 2014 levels would be required to fully offset the drought-related increase in CO_2 emissions (Hardin, 2017) and suggest that having a comprehensive and integrated energy-water management plan could help minimize CO_2 emissions during drought events. Other studies have also highlighted the potential role of increasing renewable energy resources to mitigate these drought consequences (Christian-Smith et al., 2015; Brummitt et al., 2013; Scorah et al., 2012).

Creating holistic climate change mitigation and environmental policies that provide societal benefits, without increasing the power sector's vulnerability to future climatic conditions, requires the careful consideration of the interdependencies between energy, environment and climate. While the many publications have assessed the role of renewable integration on future power sector emissions (Greenblatt, 2013; Greenblatt, 2015; Barbose et al., 2015; Walmsley et al., 2015) and cooling water use (Meldrum et al., 2013; Fthenakis and Kim, 2010; Mouratiadou, 2017; Miglietta et al., 2018) trajectories, much less attention has been directed to assessing the tradeoffs in regards to CO_2 emissions and the water dependency of the power sector, particularly during periods of extreme drought. This paper assesses the time-varying changes in the water intensity and CO_2 emissions intensity of California's grid during the period of 2010 through 2016, which was a period that includes wet periods, extreme drought, as well as technological transitions in the electricity generation fleet. The major research question investigated is whether or not the expansion of water-lean renewable electricity sources over this time-period, namely wind and solar PV, markedly reduced California's vulnerability to drought-related increases in emissions and cooling-water usage due to diminished hydropower resources. First, a brief discussion of significant policies affecting the CO_2 emissions and cooling water usage intensities of California's power sector are discussed. Second, an analysis of how statewide cooling water requirements and CO_2 emissions changed during the period between 2010 and 2016, which includes the state's unprecedented drought, is presented. Finally, a discussion of how current policies have affected the environmental performance of the grid, and its resilience to disruptions due to drought, are discussed. The results are important for identifying policies that synergistically align mitigation (i.e. reducing greenhouse gas emissions) and adaptation (e.g. increasing the power sector's resilience to drought) priorities, and by contrast, those policies that potentially pose unintended consequences to either priority. California presents an important case study because of its aggressive mitigation and environmental policy goals, as well as its susceptibility to drought and water stress.

2. An overview of recent policy initiatives affecting the environmental impacts of California's electricity sector

California's recent changes in the power sector and the evolving fuel mix have been motivated by a number of policy-driven initiatives. As part of its climate change mitigation efforts, the state of California enacted legislation to reduce greenhouse gases to 40% and 80% below 1990 levels by 2030 and 2050, respectively (Office of Governor, 2015). The 2050 goal was established in 2005 via Executive Order S-03–05, while the 2030 goal was recently enacted through Executive Order B-30-15 (Office of Governor, 2015; Office of Governor), which was signed by Governor Brown in April 2015 to accelerate the state's greenhouse gas reductions and better prepare it for reaching its 2050 goal. Based on the California Air Resources Board (CARB) climate change scoping plan, the electricity sector, one of the biggest emitters of CO_2, must reduce its carbon footprint as much as 43–61% from its 1990 level by 2030 to facilitate economy-wide targets (California Air Resource Board, 2017b).

In order to align its climate goals with the electricity sector's planning and procurement activities, the state passed Senate Bill 350 (SB 350) in 2015 to strengthen support for its statewide Renewable Portfolio Standard (RPS) targets and energy efficiency programs, which effectively shift the trajectory of future of power generation technologies across the state (California Legislative Information, 2015). California's renewable RPS, a regulatory mandate to increase utility-scale production of electricity from eligible renewable sources as defined by the California Energy Commission (CEC), includes biomass, geothermal, solar, wind, and small hydroelectric (< 30 MW) facilities across all load serving entities (i.e. investor-owned utilities, publicly owned utilities, electric service providers, and community choice aggregators) (Green, et al., 2015). While California is on track to get 33% of its retail electricity from renewable resources by 2020 as mandated by Senate Bill X1–2 (passed in 2011) (California Legislative Information, 2011), SB 350 increases this share to 50% by 2030 (Green et al., 2015).

Complimentary to the state's RPS program, the California Solar Initiative (CSI) and Self-Generation Incentive Program (SGIP) has stimulated the development of demand-side distributed renewable generation (Blackney and Lee, 2016). These programs incentivize the customer to install distributed renewable energy generation technologies that directly serve their own load. Electricity generated from power systems installed under CSI and SGIP is generally not counted towards utilities' RPS obligation. These programs have successfully supported the growth of distributed solar PV generation from 1300 GWh in 2010–9000 GWh in 2016 (California Public Utilities Commission).

The California Global Warming Solutions Act (Assembly Bill 32 or AB-32) Cap-and-Trade program became effective in 2013 and was designed by CARB to provide a backstop for the growth of statewide greenhouse gas emissions. In 2017, California, Quebec and Ontario Canada signed an agreement to create a joint carbon market, which is currently the second-largest in the world (California Air Resource Board, 2017b). The Cap-and-Trade program provides monetary incentives for greenhouse gas emitters to reduce their emissions by creating a market for polluting entities to buy and sell pollution credits. Large polluters can buy pollution credits from lesser-polluting entities, and therefore, are incentivized to become cleaner over time so that they do not need to purchase credits. California has quarterly auctions for large power plants, factories, and fuel distributors with a rising annual price floor ($13.57 per metric ton by 2017) (California Air Resource Board, 2017a). Overall limits on emissions will be reduced over time to ensure that the AB-32 target is met, by establishing a statewide cap that controls the total amount of emissions released by all market participants, with the expectation that the cap will decline over time (California Air Resource Board, 2017a; California Air Resource Board, 2017b). The program is expected to facilitate a reduction of as much as 40–85 $MMTCO_2$ equivalent in CARB's scoping plan for 2030 emissions target (California Air Resource Board, 2017b). In 2017 it was extended until 2030, beyond its initial expiration of 2020 (AB 398) (California Legislative Information, 2017a). Most of the funds from the trades are allocated for green projects in the state.

In addition to its climate change mitigation policies, California is progressive in its environmental regulations, which also impact the power sector. In response to US Environmental Protection Agency's (EPA's) Clean Water Act section 316(b) regulations (EPA, 2002), a policy affecting once-through cooled power plants was approved by California's State Water Resources Control Board (SWRCB) and took effect on October 1, 2010 to protect ocean ecosystems by reducing mortality due to the entrainment and impingement of organisms on cooling water intake screens (California Energy Commission, 2018). This policy recognizes the closed-cycle evaporative cooling system as the best available technology, and therefore, creates a benchmark for compliance requiring a 93% minimum reduction from design uptake

flow rates in once-through cooled facilities (California Energy Commission, 2018). Alternatively, existing once-through cooled plants can comply by using dry cooling system or by shutting down.

California's once-through cooling system phase-out policy affects 19 existing coastal power plants (typically units built in 1960s) and any thermal power plant built after 2010. These power plants represent about 17,500 MW of generation capacity that withdrew approximately 15 billion gallons of seawater per day prior to the passage of the policy in 2010 (California Energy Commission, 2018; EPA, 2014). By the end of 2016, about 4250 MW capacity was in compliance and 13,250 MW still had yet to comply. California's only remaining nuclear power generation units, Diablo Canyon units 1 and 2, will be retired in 2024 and 2025, respectively, which will result in 2256 MW of carbon-free baseload capacity coming offline. The state's only other nuclear facility, San Onofre, with a capacity of 2246 MW was retired in 2012 but continues to utilize 4% of its pre-retirement operating cooling water flows from the ocean during its decommissioning process (State Water Resources Control Board, 2013). The lost generation resulting from the retirement or retrofit of affected power plants will require new capacity to be built or new energy efficiency, demand response or renewable energy generation programs to offset associated reductions in capacity. From an environmental perspective, switching from once-through cooling systems to recirculating cooling systems generally result in average efficiency penalties of 1–3% for natural gas-fueled combined cycle and steam cycle units, given the increased parasitic energy use of added equipment and the switch from cold ocean water to other water sources for cooling (Jones & Stokes, 2008). The efficiency penalty can be higher for switching to dry cooled systems, which require fans for driving air-cooled condensers (Sanders, 2015). From a water use standpoint, recirculating cooling systems reduce water withdrawal volumes substantially, yet increase consumptive water losses compered to once-through cooled systems (Peer and Sanders, 2016). Therefore, switching to this technology could strain freshwater resources unless alternative sources of water such as reclaimed or recycled water are used in lieu of freshwater resources.

Since the future water supply portfolio is moving towards drought resilient local water resources, rather than long distance freshwater conveyance projects, more water recycling projects are being planned in California, especially in regards to industrial cooling systems, which are one of the largest consumers of the tertiary treated reclaimed water (Los Angeles Department of Water and Power, 2015). For example, in Southern California a 550 MW combined cycle power plant (Unit 6 of Valley Generating Station) has been using reclaimed water produced by the adjacent Donald C. Tillman Water Reclamation Plant since 2008 (Morrow et al., 2012). More power plants are planning to use reclaimed water, despite potential operational challenges such as corrosion, scaling, and biofouling within cooling towers and the boiler makeup feed system components (i.e., due to reclaimed water quality compared to freshwater quality) (Morrow et al., 2012; Sanders, 2015). In general, the cost effectiveness of switching to reclaimed water sources for cooling is determined by factors such as the distance between facilities (typically in the limits of 10–25 miles), the price of water, and safety and operational factors (Stillwell and Webber, 2014).

Collectively, these policies and technological shifts have driven extensive changes in California's electricity fuel mix, leading to a near doubling in the state's renewable electricity generation over the extent of a few years. Fig. 1 illustrates the growth of renewable energy resources, most notably wind and solar PV, between 2010 and 2016 (Blackney and Lee, 2016).

3. Methodology

A comprehensive data analysis was carried out to capture changes in the statewide CO_2 emissions and cooling water footprints of California's electricity sector resulting from recent technological transitions. Electricity generation data from 2010 to 2016 were analyzed with a bottom-up approach using monthly self-reported electricity generating unit (EGU) level data from the Energy Information Administration's (EIA) 923-Form (EIA, 2017a). Monthly EGU generation data were aggregated into five categories, including natural gas, hydropower (including both large and small hydroelectric generators), nuclear, utility-scale solar and wind (including wind turbines, solar PV and concentrated solar power EGUs), and "other" generators (including geothermal and biomass), and plotted in the bottom panel of Fig. 2. The total generation category in Fig. 2 includes generation from all utility-scale EGUs used in the power sector. Drought severity, defined in terms of percentage of state-wide coverage across five categories defined by the US Drought Monitor, is also plotted on the right axis of Fig. 2 across the study period of interest (National Drought Mitigation Center, 2018).

Approximately half of California's in-state generation comes from natural gas generators, and these generators are more diverse, on average, than other fossil fuel generators, spanning steam-cycle, combined-cycle and gas turbine generators. Since the majority of California's non-natural gas generation is CO_2 emissions free at the point of generation (with the exception of biomass/biogas generators), natural gas generators are the most consequential from an emissions perspective. Likewise, since natural gas generators represent the majority of thermal power plant generation across the state, they also have the largest cooling water consumption consequences, especially given the recent and planned retirement of the state's two nuclear power plants. The EIA-923 EGU database reports 96.9 TWh of natural gas-fired generation across California in 2016 (comprised of 78 TWh from combined cycle, 4 TWh from steam cycle, 14 TWh from combustion gas turbine and 0.7 TW from internal combustion generators and the rest from the other types of generators), covering about 98% of the reported in-state natural gas fleet based on data from CEC (California Energy Commission, 2017c).

The top panel of Fig. 2 illustrates statewide CO_2 emissions and cooling water usage intensity metrics, which represent the average CO_2 emissions and cooling water use embedded in a unit of electricity generated in California, respectively. The average statewide CO_2 emissions intensity factor was estimated by dividing aggregated in-state emissions from CO_2-emitting power generators (i.e., natural gas and bio-based fuels) by total in-state, utility-scale generation in each month (See Fig. 2). Monthly CO_2 emissions footprints were calculated for each power plant by multiplying a fuel-specific CO_2 emissions factor by monthly EGU-level primary fuel consumption. For CO_2 emissions estimation, EPA's default CO_2 emissions factors were used for each fuel type (53.02 kg CO_2/MMBtu for natural gas and biogas, 93.80 kg CO_2/MMBtu for wood and wood residuals, and 118.17 kg CO_2/MMBtu for agricultural byproduct) (EPA, 2009).

Four average statewide cooling water consumption intensity metrics were calculated for natural gas and nuclear power plants cooled with freshwater, reclaimed, ocean, and "other" cooling water (including brackish, groundwater or multiple sources). The total cooling water consumption intensity metric represents the sum of all four metrics. Statewide cooling water intensity metrics were calculated by aggregating cooling water consumption across all facilities and dividing by total monthly generation for each cooling water source type. The cooling water usage of other types of thermal generators, including many geothermal, CSP and biomass facilities, was not included in this analysis, since these generators are typically small and/or utilize dry cooled systems. Cooling water sources reported in the EIA-860 (EIA, 2017b) were cross-checked with CEC water supply data to ensure data integrity (California Energy Commission, 2015).

Monthly plant-level cooling water consumption across water cooled facilities in California were calculated for each power plant by multiplying a cooling water consumption factor by monthly EGU-level electricity generation data based on each power plant's unique fuel, prime mover (steam turbine or combined cycle) and cooling system (once-through and recirculating) configuration. In this assessment, we relied on median cooling water consumption rates reported in (Peer and

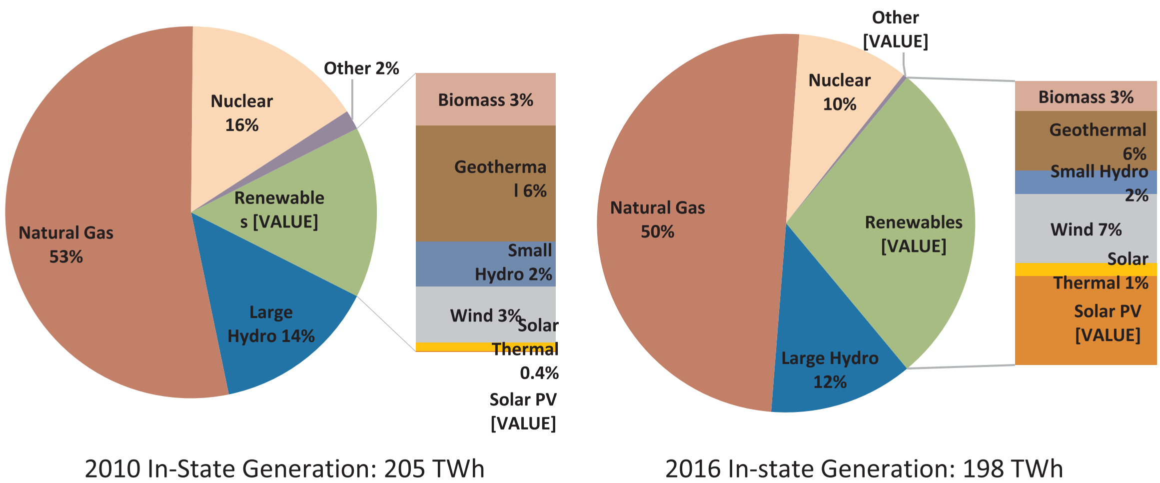

Fig. 1. California 2010 and 2016 in-state electricity generation fuel mix (California Energy Commission, 2017d). This figure only includes utility scale renewable electricity, thus, distributed renewable electricity generation is omitted.

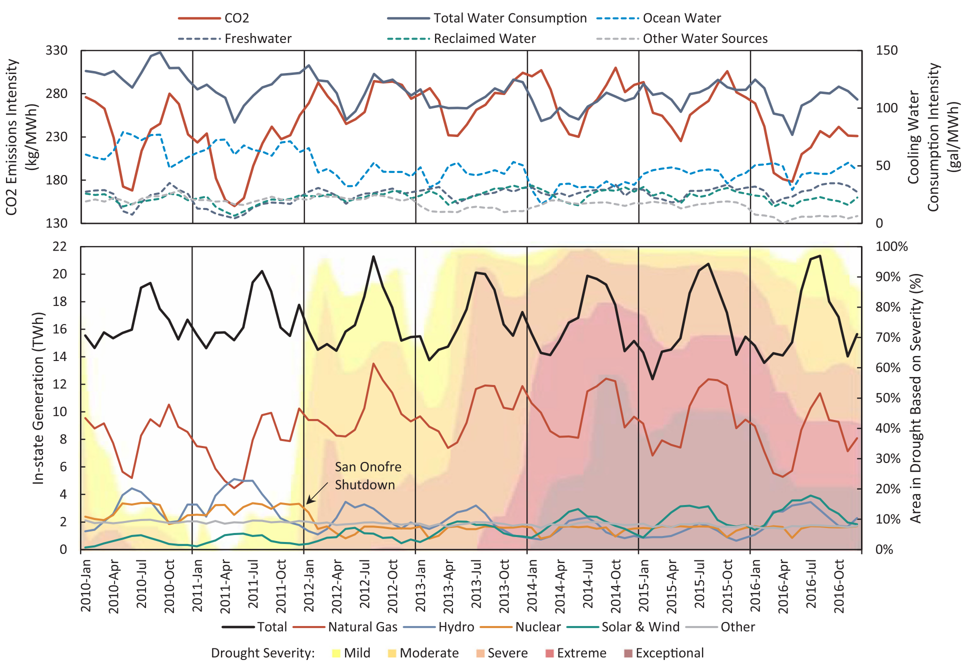

Fig. 2. California's average statewide CO_2 emissions and cooling water consumption intensities (top) and monthly electricity generation by fuel and percentage of state-wide area in drought (bottom). Generation values reflect aggregated monthly generation by fuel based on the EIA-923 form (EIA, 2017a). Average statewide CO_2 emissions and cooling water consumption intensities are calculated by dividing total in-state carbon emissions and cooling water consumption by total in-state generation, ignoring imports.

Sanders, 2016), which are based on a statistical analysis of EIA cooling water rates, with the exception of natural gas steam cycle units where we used cooling water consumption factors from (Macknick et al., 2011). Cooling water consumption values were only calculated for nuclear and thermal natural gas-fired power plants with reported cooling system technologies in EIA-923. Approximately 81% of 2016 total natural gas thermal generation (i.e. steam and combined cycle units) reporting generation also reported their cooling system type (including dry-cooled facilities); the rest did not report cooling system data to the EIA. However, most of the units that have missing cooling system data in EIA-860 are combined heat and power (CHP) units (See Fig. 1 in Supplementary material). The steam turbine portion of CHP units typically represent a smaller share of unit's total generation (17% on average for CHP units compared to 33% standard non-CHP combined cycles, based on EIA-923 data (EIA, 2017a)); therefore, CHP units generally have a smaller cooling load compared to conventional non-CHP units. Moreover, some of the heat generated within the CHP unit is used for downstream processes, further decreasing cooling water needs. As a result, this analysis considers 81% of statewide, water-cooled natural gas thermal generation and 100% of nuclear generation, thereby omitting a significant fraction of CHP generators because of uncertainty regarding their net cooling water usage, which is expected to be considerably less than a non-CHP unit.

In addition to some uncertainties and inconsistencies between data sources and missing data, there are several simplifying assumptions worth mentioning. CO_2 emissions were only calculated at the source of generation, thus neglecting any emissions associated with upstream fuel production and processing, delivery, and transmission and distribution infrastructures. Moreover, only CO_2 emissions associated with in-state generation assets are taken into account, so there were not any adjustments made to estimate the emissions (or cooling water usage) embedded in imported and exported amounts of electricity. In terms of water use, we limited our analysis to cooling water consumption only, which is the amount of water that is ultimately removed from a power plant's original water basin (in this analysis, as evaporative losses) for cooling purposes and is, thus, consequential from a water management perspective. Water withdrawals were not studied since they are most consequential for once-through cooled power plant facilities and all once-through facilities in California are coastal power plants using seawater for cooling, and will ultimately be phased out according to the

abovementioned once-through cooling phase-out policy. For recirculating and dry-cooled power plants operating in California, cooling water consumption and water withdrawals are close in magnitude (Peer and Sanders, 2016). We also did not include evaporative losses from hydropower facilities, as the analysis was restricted to water utilized for cooling needs.

4. Results

Fig. 2 illustrates that seasonal trends in supply-side resource availability, as well as seasonal fluctuations in electricity demand, affect trends in monthly statewide CO_2 emissions. The average CO_2 intensity of the grid is heavily dependent on the relative fraction of natural gas generation to carbon-free generation, as the relative amount of other carbon-based fuels such as biomass and biogas are very small in comparison. Consequently, statewide CO_2 intensity does not scale with total generation in months when high fractions of carbon-free generation are available. It generally peaks when hydro and variable renewable generation resources are low, typically in the periods between September to November. Carbon-free resources tend to be most abundant during hot months in California, offsetting some of the environmental repercussions of high electrical space-cooling loads.

The study period highlights a few major trends in terms of CO_2 emissions intensity of California's electricity sector. The emissions intensity spiked significantly in 2012 as a result of the San Onofre nuclear shutdown, when natural gas generation increased sharply to make up for lost generation. The increases were exacerbated by the concurrent drop in hydropower availability compared to 2011 due to drought. The significant expansion of solar PV and wind electricity in years following 2012 offset subsequent spikes in natural gas generation, despite the fact that the drought continued to worsen across 2014 and 2015. The state's electric power sector's CO_2 emissions intensity dropped significantly in 2016, in part because of ample hydroelectricity generation, but more importantly due to large increases in renewable generation. In 2016, the annual average emissions intensity was calculated to be 221 $kgCO_2$/MWh, which is slightly lower than the 2016 eGRID total output emissions rate of 240 $kgCO_2$/MWh for Western Electricity Coordinating Council – California; whereas, the national level CO_2 emissions intensity of electric power sector was 453 kg/MWh in the same year (EPA, 2018).

The generation trends point to an interesting similarity in terms of the seasonal variability of hydroelectric, wind, and solar resources. Hydroelectricity is generated as water flows through California's rivers, as well as when the water is released from reservoirs, which often occurs after the winter's wet season. Hydroelectricity production generally rises in the late spring and early summer months when runoff from melting snowpack deposited during the winter is high (Gleick, 2016). Tarroja et al. (2016) studied the future impacts of climate change on California's reservoir inflows using the CMIP5 model under two Representative Concentration Pathway scenarios (RCP) of RCP 4.5 and RCP 8.5, using an integrated model of major surface water reservoirs and electric grid dispatch. They showed that average annual hydropower generation might decrease by 3.1% under RCP4.5 and remain almost unaffected under the RCP8.5 scenario. While climate change simulations indicate more reservoir inflow, these increases might cause more reservoir spillage of water due to extreme inflow events (Tarroja et al., 2016). Moreover, under warmer climate conditions, the timing of snowmelt and streamflow runoff is expected to shift earlier in the seasonal cycle (Dettinger et al., 2004).

The state's wind turbines and solar generators show the highest capacity factors during the periods of April to June and April to August, respectively and the lowest capacity factors in the late fall and winter months (Hingtgen et al., 2017; EIA, 2018). These synergies are advantageous as wind and solar generation can make up for lost hydropower generation during drought events, as was demonstrated in 2015 when the growth of wind and solar generation was able offset some of the losses in hydropower capacity during the summer. These seasonal couplings effectively reduced the magnitude of the natural gas generation that was required to make up for the lost hydropower. However, the combination of these three variable sources can also be difficult to manage in very wet years, when large spring and summer runoff volumes translate into large hydropower resources. For example, in 2017, following the wet 2016/2017 winter, solar and hydropower generation resources were very high during periods of relatively low demand; as a result, wholesale power market prices dipped below zero at times, forcing grid-operators to curtail variable wind and solar generation resources (California Independent System Operator, 2017; Denholm, et al., 2015).

The total statewide cooling water consumption intensity of California's power sector has dropped over the studied period. One of the largest reasons for this decrease was because of the retirement of the San Onofre nuclear power plant. Although three natural gas ocean-cooled power plants retired to comply with the once-through cooling phase-out policy in 2010 and 2011 (Humboldt Bay 1 and 2, Potrero 3, and South Bay representing 637 MW of aggregated capacity) (California Energy Commission, 2018), the significant drop in the ocean water consumption intensity was related to the San Onofre shutdown as it was a much bigger power plant in terms of generation. The retirement of the ocean-cooled San Onofre nuclear power plant reduced the grid's overall ocean cooling water consumption intensity. While the freshwater and reclaimed cooling water intensities of the grid increased unintentionally as a result of increasing natural gas generation, the net impact at the state level was a decrease in the total water consumption intensity of the grid since the cooling water consumption rate of the retired nuclear power plant was more than the natural gas generators that replaced its generation. After this retirement, the total cooling water intensity metric remained relatively constant over the drought period from 2012 until the end of 2015 and then dropped again in 2016, due to large contributions of electricity from hydropower, solar and wind. Thanks to these water-lean technologies, California has a relatively small cooling water consumption footprint on the order of 114 gal/MWh, which is much lower than the national average of 404 gal/MWh based on 2015 U.S. Geological Survey estimates (Dieter, 2018).

Most of the natural gas generation fleet is dominated by combined cycle units that are generally newer, and therefore, not cooled with once through cooling systems that utilize ocean water. As a result, freshwater and reclaimed cooling water consumption intensities were generally higher in dry versus water-rich years during the study period because of the increased dependence on natural gas generators when hydropower resources were low. However, the highest fresh and reclaimed cooling water intensities during the period of study actually occurred in 2010, in spite of the fact that there were no significant drought conditions. During this year, San Onofre was still operational and the penetration of water-lean renewables was still relatively low, compared to later wet years (e.g. 2016). Fig. 2 also illustrates a significant drop in generation for “Other Water” category in 2016 because of a few big generators on the coast, which reported water type code, “Other”, in EIA-860 for all pre-2016 years and ocean cooled in 2016.

Because of the significance of natural gas on the environmental impacts of California's power sector, net changes in monthly generation, CO_2 emissions, and all types of consumed cooling water volumes during the period of study were aggregated at the power plant-level for the years 2010 and 2016 for in-state natural gas generators. Values from the base year, 2010, were subtracted from 2016 and the changes were mapped spatially in Fig. 3, such that symbols in green and red indicate generators experiencing a net decrease or increase in the proxy of interest in 2016 compared to 2010, respectively. In 2016, annual CO_2 emissions and cooling water usage from natural gas generation dropped by around 6 million tons and 7 billion gallons, respectively, from the base year levels (i.e. 2010). However, these changes were not evenly distributed throughout the state. Larger amount of CO_2 emissions and

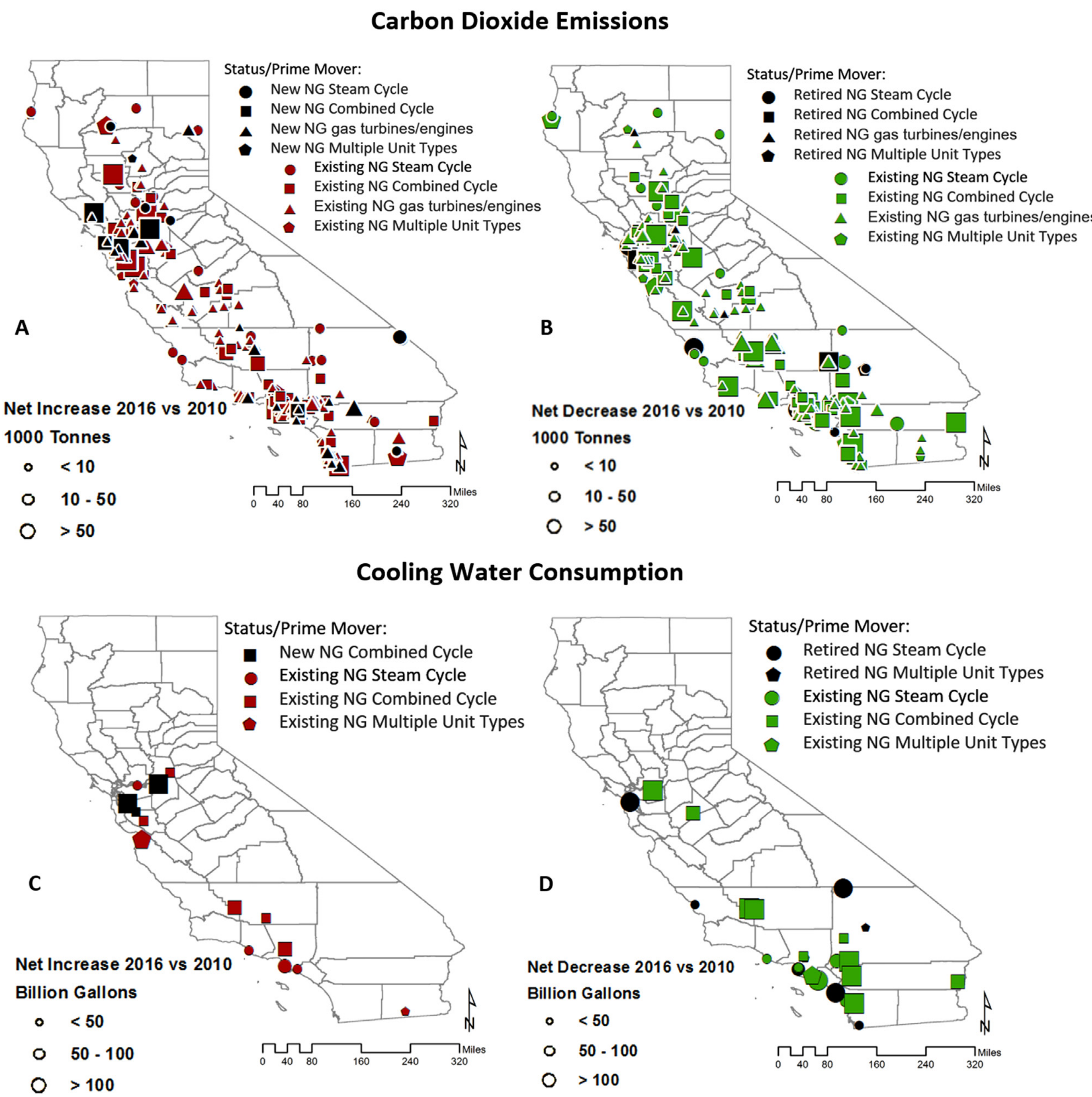

Fig. 3. Net changes in CO_2 emissions (increase in A, decrease in B) and cooling water consumption (increase in C and decrease in D) across California's natural gas electricity generation fleet in 2016 versus 2010. Each shape represents a power plant categorized into five categories, i.e. combined cycle, steam cycle, gas turbine, internal combustion engines and power plants with multi-type prime movers.

cooling water consumption occurred in power plants located in the urban regions of Northern and Southern California; whereas, Central California mostly experienced smaller changes in either metric. From a technology standpoint, significant emissions and cooling water use changes occurred across combined cycle power plants, which have operated more flexibly in recent years to balance renewables.

5. Discussion

As climate change is expected to increase the probability of severe drought conditions in California (Diffenbaugh et al., 2015), improving the drought resiliency of the state's evolving power system has become more important to the success of its long-term mitigation and adaptation strategies. Changes in state policies, market conditions, hydrological variation, and environmental priorities have shaped an evolving fleet of generation resources, which have varying environmental consequences. Much of California's ability to shift its generation resources so quickly can be attributed to the way that its electricity generation resources are procured. Unlike some markets, California's Independent System Operator (CAISO) operates by dispatching resources from the cheapest to expensive ones after granting priority to energy efficiency, demand response, renewables, and distributed generation, respectively, reflecting California's prescribed loading order (Bender et al., 2005). Increasing renewable electricity generation has been established as a major policy priority to meet the state's long-term goals towards deep decarbonization (Mahone et al., 2018.), which will decrease the state's reliance on natural gas (decreasing greenhouse gas emissions) and reduce pressure on the freshwater intensity of the grid by promoting the quick expansion of water-lean solar PV and wind capacity. In this section, these trends are discussed in regards to the trajectory of the grid's

environmental performance and resilience to water disruptions during times of drought.

5.1. The impact of growing renewable energy capacity on environmental performance and drought resilience

Renewable energy sources vary in terms of their water demands. Given the fact that solar PV and wind energy require no cooling, they are water-lean electricity generation technologies (Fthenakis and Kim, 2010; Dodder et al., 2016). Thus, a large water resource is not a requirement in their production sites, aside from water for washing PV panels (Sanders, 2015). Therefore, in addition to emissions benefits, the expansion of these resources makes the power system less vulnerable to water scarcity and drought events. The seasonality, particularly of solar PV, is beneficial to increasing the grid's resilience to drought by increasing water-free and carbon-free sources during peak summer demand when water resources tend to be most limited. In summer 2013, wind and solar renewable generation exceeded hydroelectricity generation and remained higher thereafter, even in 2016, after the end of four-year drought.

Some renewables such as concentrated solar power, geothermal and biomass require cooling since they utilize thermal cycles. Although the water requirements of these generators are not accounted for in Figs. 2 and 3, the statewide water requirements for these generators would likely be small compared to natural gas generators, as they represent only 10% of total in-state generation. Furthermore, many of these facilities are dry-cooled, meaning that they use air-cooled condensers rather than water to condense steam exiting a steam turbine. Similarly, many geothermal facilities are cooled using their own formation water, and thus, might not be utilizing water that would be subject to competition across other industries (Clark et al., 2013).

Fig. 4 illustrates the locations of qualifying renewable energy facilities in California, plotted over a base map of water stress from World Resources Institute to give further context to the expansion of renewable electricity generation with regard to baseline water stress risk factors. The baseline water stress measures the ratio of total annual water withdrawals to total available annual renewable supply (UC Davis Sustainability Indicators Group, 2013). Accordingly, each renewable power plant was separated into three groups: technologies requiring cooling water (i.e. biomass, concentrated solar and geothermal plants), technologies that do not require cooling water (i.e. wind and solar PV), and small hydropower plants (≤ 30 MW). Large hydropower plants were not included in Fig. 4, as they are not included in the state of California's definition of eligible renewable energy resources for its RPS (Green et al., 2015). (Note that the hydropower category in Fig. 2, by contrast, includes both small hydropower and large hydropower.)

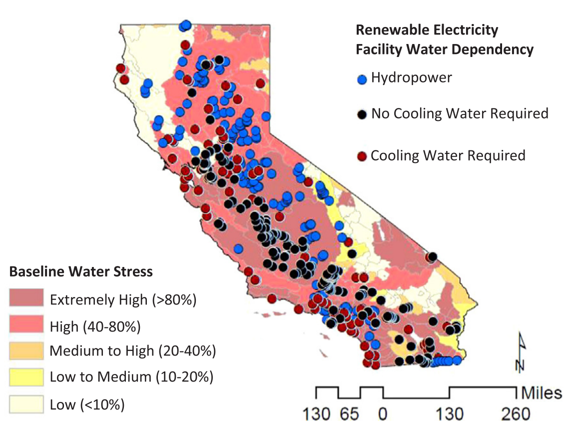

Fig. 4. RPS-eligible renewable electricity generation in 2016 shown on baseline water stress map. Based on water use, power plants are specified in three groups: small hydropower plants, biomass, geothermal and solar concentrated power plants requiring cooling water, and the power plants that do not require cooling water i.e. solar photovoltaic and wind turbines. Electricity generation data from CEC Almanac (California Energy Commission, 2017d), location data from EIA-860 (EIA, 2017b), and baseline water stress risk map from World Resources Institute (UC Davis Sustainability Indicators Group, 2013).

The map of renewable energy facilities in Fig. 4 shows that plants that do not require cooling water (mostly wind and solar PV) are generally sited in regions of high risk water stress areas. These generators produce emissions-free generation without exacerbating existing water stress, providing resilience to drought. However, there are also many small hydropower facilities located in high risk regions that might be subject to vulnerability to drought events.

5.2. The impact of a shifting natural gas fleet on environmental performance and drought resilience

California's cleaner energy future has driven the state's natural gas fleet towards more flexible generators by replacing old and inefficient steam cycle units with more efficient and less water intensive combined-cycle units. Total natural gas electricity generation decreased by 8800 GWh in 2016 compared to 2010, after substantial increases in the drought period spanning 2012–2015. However, these high-level numbers do not reveal insights regarding shifts in the nature of generation technologies that affect the environmental consequences of the fleet. California added 20 GW of natural gas combined cycle nameplate capacity between 2001 and 2016. In 2016, this 20 GW of capacity accounted for 45% of the total natural gas fleet and led to a 23% statewide thermal efficiency improvement across the state's natural gas fleet (between 2001 and 2016), which has remained at the same level for the past four years (Nyberg, 2018). During the studied period, 8217 MW of natural gas capacity was added and 5856 MW of capacity was retired. Of the added capacity, 13 new combined cycle power plants were added with total capacity of 3572 MW, and the remaining capacity included new gas turbines and internal combustion engine units (4645 MW total). (Note that only power plants that were reporting natural gas as their primary fuel have been accounted). In the same period, one older combined-cycle power plant and 17 steam cycle units were retired with total capacity of 624 MW and 4815 MW, respectively, and the rest of the retirements were either gas turbine or internal combustion engine units. As variable renewable generation (prioritized before natural gas facilities in the state's loading order) has grown, these newer, more efficient and cheaper combined cycle units have functioned increasingly as flexible load-following units that can ramp up and down to accommodate planned changes in supply versus demand. Accordingly, the capacity factors of these generators fell from 51% in 2010 to 41% in 2016 (Nyberg, 2018).

The increasing share of renewable electricity across California's grid has resulted in capacity additions of fast-acting backup generators that can smooth out the intermittency of renewable energy generation in response to fast-changes in variable loads. Consequently, more natural gas combustion turbines have operated as peaker units in recent years. In 2016, the state had 78 plants with 3898 GWh of net generation, compared to 68 plants with 848 GWh of annual generation in 2010 (Nyberg, 2018; Nyberg, 2011). These power plants are normally inefficient, fast-ramping simple-cycle combustion turbines that are required to operate less than 1300 h of annual operation under Rule 2012- Protocol for Monitoring, Reporting, and Recordkeeping for Oxides of Nitrogen (NO_x) Emissions to comply with NO_x emissions regulation (Coats, 2011).

The once-through cooling phase-out policy has accelerated the natural gas fleet's modernization through the retirement of older natural gas steam cycle generators using once-through cooling systems with seawater. However, the state must be cognizant in the process of replacing or repowering these existing generators, that switching to recirculating cooled or even dry cooled generators could increase the freshwater cooling needs of these power plants, since ocean water is not

a viable option for these cooling systems. However, the state is actively promoting the usage of reclaimed water for cooling any replacement coastal capacity, and most units are using dry cooling systems to minimize their overall cooling water consumption and water withdrawal footprint (Electric Power Research Institute, 2003). (While reclaimed water is the preferred water source to minimize freshwater consumption, using reclaimed water cooling can raise operational costs due to fouling and potential water treatment (Barker and Stillwell, 2016; Electric Power Research Institute, 2006).)

Regardless of its impact on total statewide cooling water consumption across California's electricity sector, the implementation of the state's once-through cooling phase-out policy will be followed by meaningful reductions to ocean ecosystem risks, as pulling in water into once-through cooling systems can cause entrainment (i.e. drawing fish, eggs, and shellfish larvae into the system) and entrapment (i.e. pinning organisms across intake screens) (Sanders, 2015). However, another ancillary benefit will be to reducing thermal pollution discharges into the marine environment. The EPA regulates these thermal discharges by enforcing cooling water thermal discharge limits under Section 316(a) of the Clean Water Act (EPA, 2008). Although the thermal discharge limits established by the Clean Water Act's National Pollution Discharge Elimination System vary according to state, they typically require that thermal discharges remain below 90°F. A recent analysis of EPA data found that 3 out of 35 total incidents of exceeded discharge temperatures occurred in once-through cooled gas-fired steam cycle power facilities in California, namely the AES Redondo Beach, AES Alamitos and Huntington Beach facilities between January 2012 and December 2015 (Mccall et al., 2016).

5.3. The impact of nuclear retirements on environmental performance and drought resilience

Despite these environmental achievements, the retirement of San Onofre caused a large shift towards natural gas generation in 2012, which increased the carbon intensity of the grid and its fresh cooling water consumption (see Fig. 2 and Table 1). Although peaks in the statewide emissions intensity following this event have trended downward since, the San Onofre retirement slowed the state's overall decarbonization efforts. Even with current levels of renewable generation, the CO_2 intensity of the grid is still sensitive to the relative amount of hydroelectricity available; in other words, existing renewable energy sources alone are not yet (i.e. as of the end of 2016) able to maintain CO_2 emissions intensity levels below those prior to the San Onofre nuclear shutdown in 2012. In terms of cooling water consumption, San Onofre nuclear shutdown caused more reliance on freshwater because of increased cooling loads across natural gas thermal generation (see Table 1).

The loss of emissions-free generation following San Onofre's retirement raises important questions regarding the effect that the Diablo Canyon nuclear plant shutdown in 2024 will have on CO_2 intensity of the California's generation mix. Although the state plans to replace its capacity with energy efficiency and renewable resources, there is not a one to one relationship in the carbon-free generation resulting from replacing one unit of nuclear capacity with a unit of wind or solar PV renewable energy capacity because of large differences in capacity factors. Diablo Canyon's nominal capacity factor is 90% (EIA, 2017b), while the average capacity factor for wind and solar PV generation across the state are 26% and 23% (California Energy Commission, 2017d; Hingtgen et al., 2017), respectively. In other words, more variable renewable electricity capacity must be added to replace the capacity lost by the nuclear generators because they only operate a fraction of the time that a nuclear facility typically operates. Although Pacific Gas and Electric Company plans to replace Diablo Canyon by procuring new energy efficiency projects and GHG-free energy, this plan has been challenged by California Public Utilities Commission (2018).

Table 1
Natural gas and nuclear generation requiring cooling water decreased during 2010–2016. All data in TWh[a]. Data represent 81% and 100% of total in-state water-cooled natural gas and nuclear generation, respectively. The majority of missing cooling water data were for natural gas CHP units, whose water use are unknown.

Year	Freshwater	Reclaimed Water	Ocean Water	Other Water	**Total Water**
2010	21.4	20.1	39.0	18.1	**98.4**
2011	12.3	16.1	42.1	15.0	**85.5**
2012	23.8	21.9	29.6	18.4	**93.6**
2013	24.5	23.7	27.6	15.5	**91.3**
2014	25.6	23.5	24.8	15.8	**89.6**
2015	23.8	22.9	26.1	14.9	**87.7**
2016	24.4	18.0	27.9	5.0	**75.3**

[a] Only includes generation from facilities that reported water usage in (EIA, 2017a) and (EIA, 2017b).

5.4. The impact of growing demand-side programs on environmental performance and drought resilience

One of the greatest achievements in California's electricity sector, has been its ability to maintain relatively stable levels of annual demand, despite population growth (Kavalec et al., 2016). This trend has been supported by aggressive energy efficiency policies (California Energy Commission, 2017b; Reyna and Chester, 2017), the massive expansion of privately and community-owned distributed generation, access to alternative providers through Direct Access or Community Choice Aggregation (Jones et al., 2017), and demand response programs (Kavalec et al., 2016). At the same time, policies incorporating higher renewable penetration require higher fractions of flexible generation in the grid. In terms of policies promoting emissions- and water-reductions, these resource alternatives and demand-side interventions provide cost-effective means of reducing the need for installing more resource-intensive generation, thereby eliminating all of the upstream lifecycle environmental impacts associated with those abated resources as well.

More recently, the deployment of self-generation and distributed energy resources on the consumer or “demand-side” of the power grid has continued to placate the need for new generation resources to meet increases in demand. However, new challenges such as the “duck curve” have emerged and will need to be addressed as more variable renewable generation comes online. The duck curve refers to the challenge that CAISO faces as more and more solar PV resources come online and markedly reduce the need for conventional resources during the day; however, as solar PV quickly goes offline as the sun goes down, large, fast-acting ramping resources are needed to quickly meet peak demand, over a very short time, in the early evening (Denholm et al., 2015). If these ramping resource requirements are all met by fast acting, but dirty combustion natural gas generators, the emissions benefit of renewable energy integration will be reduced. New policies to promote demand-side programs and market drivers to increase (and decrease) the use of electricity when renewable resources are available (or not available) are needed and some steps have already been taken. Activating third party and community choice aggregators (e.g. via AB 117) (California Legislative Information, 2002), demand response programs (e.g. via Rulemaking (R.) 13-09-011 (Public Utilities Commission, 2016)) and mandatory storage for investor-owned utilities (e.g. via AB 2514 (California Legislative Information), AB 33 (Information), CPUC Resolution E-4586 (California Public Utilities Commission) and AB 2868 (California Legislative Information)), are all options that will help solve some of the issues.

Concerns over the potential electricity supply reliability risks associated with natural gas supply shortages might also accelerate the adoption of energy storage (e.g., utility-scale batteries), which also

serves as a means of mitigation (i.e., by increasing renewable electricity generation potential). These concerns rose in recent years after the Aliso Canyon Natural Gas Storage Facility, which is located in Southern California, experienced a leak that resulted in a 64% loss of Southern California Gas Company's natural gas inventory and a 51% loss of natural gas-withdrawal capacity in 2015, posing a moderate threat to electric reliability (Zhao et al., 2018; The Federal Energy Regulatory Commission, 2018). Thus, to ensure energy reliability in Los Angeles Basin, the CPUC directed Southern California Edison to procure both utility-owned and third-party storage resources to address the resulting generator shortages (e.g. via Resolution E-4791 (California Public Utilities Commission, 2016)).

6. Conclusion

The goal of the study was to analyze: 1) how climate change mitigation and other environmental policies in California's power sector are affecting its vulnerability to extreme drought, and 2) how drought has affected the state's progress on climate change mitigation. We quantified the state's CO_2 emissions and cooling water consumption trends as proxies for greenhouse gas emissions mitigation and water-related vulnerability of the power system, respectively, during the period of 2010–2016 and derived a few notable insights:

- In dry years when hydropower generation was low, natural gas generation was generally high to accommodate hydropower losses, markedly increasing the CO_2 emissions intensity and cooling water requirements of the grid, particularly during the hot season.
- Freshwater and reclaimed cooling water requirements scale with natural gas generation, so they tended to be highest when hydropower and renewable generation were both low, particularly during hot months of high electricity demand when freshwater availability is lowest.
- As penetrations of solar PV and wind increased throughout the period of study, they mitigated some need for increased natural gas generation in seasons when hydropower was abnormally low because their availability generally tracks hydropower availability.
- Most of the drop in the cooling water consumption intensity of electricity generation was a result of reduced power plant cooling with ocean water due to the phasing out of once-through cooling systems, most notably, the San Onofre Nuclear Power Plant (The total state-wide cooling water consumption intensity dropped from 116 gal/MWh in 2011 to 100 gal/MWh in 2016). The plant's closure also caused a steep increase in the CO_2-intensity of California's electricity generation sector; even with high hydropower and renewable electricity resource availability in 2016, the overall emissions intensity of the power sector had not yet dropped below levels prior to the San Onofre nuclear power plant retirement in that year. (The state-wide CO_2 emissions intensity rose from 207 kg/MWh in 2011 to 221 kg/MWh in 2016).
- From emissions standpoint, hydroelectricity and nuclear generation still provide significant fractions of emissions-free electricity in California but at the expense of strong water dependency and impacts to the marine environment, respectively.

These insights illustrate that increasing penetrations of wind and solar PV can meet climate change mitigation priorities while reducing the grid's vulnerability to water-related disruptions in dry years by decoupling its dependence on hydroelectricity and thermal power plants requiring water for cooling. The state's prioritization of energy efficiency and demand response, with renewables, in its loading order further support the decoupling between electricity generation and water consumption. However, the closure and planned closure of the state's two nuclear power plants present big challenges to the state's decarbonization efforts, since they operate with annual capacity factors that average more than three times those of variable renewable energy resources. While phasing out once-through cooling by coastal power plants provides benefits to marine ecosystems by ceasing all cooling-related withdrawals and thermal discharges, the state must be cognizant that this lost generation capacity is not replaced with generators that exacerbate existing freshwater stress. This study underscores the importance of evaluating climate mitigation, climate adaptation, and environmental tradeoffs holistically.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.09.014.

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